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Surprisingly Modest Water Quality Impacts From Expansion and Intensification of Large-Sscale Commercial Agriculture in the Brazilian Amazon-Cerrado Region

Christopher Neill[1,2,3], KathiJo Jankowski[2], Paulo M. Brando[1,4], Michael T. Coe[1,4], Linda A. Deegan[1,2,3], Marcia N. Macedo[1,4], Shelby H. Riskin[3], Stephen Porder[3], Helmut Elsenbeer[5], and Alex V. Krusche[6]

Abstract

Large-scale commercial cropping of soybeans expanded in the tropical Amazon and Cerrado biomes of Brazil after 1990. More recently, cropping intensified from single-cropping of soybeans to double-cropping of soybeans with corn or cotton. Cropland expansion and intensification, and the accompanying use of mineral fertilizers, raise concerns about whether nutrient runoff and impacts to surface waters will be similar to those experienced in commercial cropland regions at temperate latitudes. We quantified water infiltration through soils, water yield, and streamwater chemistry in watersheds draining native tropical forest and single- and double-cropped areas on the level, deep, highly weathered soils where cropland expansion and intensification typically occurs. Although water yield increased four-fold from croplands, streamwater chemistry remained largely unchanged. Soil characteristics exerted important control over the movement of nitrogen (N) and phosphorus (P) into streams. High soil infiltration rates prevented surface erosion and movement of particulate P, while P fixation in surface soils restricted P movement to deeper soil layers. Nitrogen retention in deep soils, likely by anion exchange, also appeared to limit N leaching and export in streamwater from both single- and double-cropped watersheds that received nitrogen fertilizer. These mechanisms led to lower streamwater P and N concentrations and lower watershed N and P export than would be expected, based on studies from temperate croplands with similar cropping and fertilizer application practices.

Keywords

water, quality, agriculture, intensification, impact

The region centered on the boundary between the Amazon and Cerrado biomes in Brazil represents the largest zone of recent agricultural expansion on earth. By the mid 2010s, more than 750,000 km^2 of the Brazilian Amazon and 830,000 km^2 of the Cerrado had been deforested (Macedo et al., 2012; Sano, Rosa, Brito, & Ferreira, 2010; Spera, Galford, Coe, Macedo, & Mustard, 2016). The expansion of croplands, overwhelmingly for soybeans, drove this large-scale land use conversion. In the state of Mato Grosso, which lies at the heart of this cropland region, the area of soybean cropland increased from less than 20,000 km^2 in 1990 to 75,000 km^2 in 2013. This produced a 12-fold increase in

[1]Woods Hole Research Center, Falmouth, MA, USA
[2]Marine Biological Laboratory, Woods Hole, MA, USA
[3]Brown University, Providence, Rhode Island, USA
[4]Instituto de Pesquisa Ambiental da Amazônia, Lago Norte, Brasilia, Brazil
[5]University of Potsdam, Am Neuen Palais, Potsdam, Germany
[6]Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Piracicaba, SP, Brazil

KathiJo Jankowski is currently at United States Geological Survey, 2630 Fanta Reed Rd., LaCrosse, WI, 54603, USA.
Shelby H. Riskin is currently at Toronto, Canada.

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Corresponding Author:
Christopher Neill, Woods Hole Research Center, Falmouth, MA 02540-1644, USA.
Email: cneill@whrc.org

soybean production from less than 2 million Mt y^{-1} to more than 24 million Mt y^{-1}.

This output was made possible by the development of tropical soybean varieties, liming and fertilization regimes that overcome low native soil pH, high soil aluminum, low phosphorus (P) fertility, and minimum-tillage practices that preserve the structure of the deep, highly weathered high-clay soils on which most cropping now occurs. Expanded production from this region fueled Brazil's rise to become the world's largest soybean-exporting nation. In 1997, Mato Grosso exported less than 2 million Mt of soybeans. By 2012, that total rose to more than 10 million Mt, with nearly 7 million Mt destined for China (Neill & Macedo 2016).

The intensification of cropping practices followed quickly on the heels of this cropland expansion. Beginning about 2000, producers began shifting from single-cropping of soybeans to double-cropping in which a second late-season crop (most commonly corn, but also cotton) follows soybean harvest within a single 6-month rainy season. In 2001, only 5,000 km^2 of Mato Grosso's 33,000 km^2 of commercial cropland were double-cropped, but by 2011 that area had expanded more than five-fold to 28,000 km^2 of the state's 58,000 km^2 of cropland. The soy–corn rotation accounts for nearly 92% of double-cropping in Mato Grosso (Spera et al., 2014; Spera, 2017). This intensification of cropping is important because it has the potential to increase food production on already cleared land, thus reducing the need for future deforestation.

Although more intensive cropping has the potential to reduce deforestation when coupled with effective land-clearing regulations, it also can sharply increase the environmental impacts of commercial agriculture (Goldsmith 2017). Soybean cropping in the Amazon-Cerrado region uses approximately 40 to 50 kg ha^{-1} of phosphorus (P) fertilizer per year but little or no nitrogen (N) fertilizer because of the N-fixing ability of soybeans. The addition of a late-season corn or cotton crop greatly increases the application of N fertilizer (typically to 60 kg N ha^{-1} or more) because of the N requirements of these second crops.

The effects of fertilizer-intensive commercial agriculture on water quality are a global concern. It is well known that the movement of N from commercial croplands to surface fresh waters often degrades water quality in temperate regions (Carpenter et al., 1998; Galloway et al., 2003; Xu et al., 2014). While control of P in runoff has been viewed as critical to avoiding impacts to fresh waters, the "P only" paradigm is likely overgeneralized and many aquatic ecosystems respond to N as well (Paerl et al., 2016). Additional N inputs have the capacity to impact both the streams that pass through this intensifying landscape and the coastal areas to which they eventually drain.

We investigated the consequences of the replacement of tropical evergreen forest with soybean cropland and the subsequent intensification of cropping from single-cropping of soybeans to double-cropping of soybeans with corn at Tanguro Ranch in eastern Mato Grosso (12°50'30", 52°23'22"). Tanguro Ranch has low topographic relief and Oxisols with moderate clay contents that are typical of the areas where commercial cropping has expanded in the broader Amazon-Cerrado region. Tanguro Ranch has large areas of single-cropped soybeans, double-cropped soybeans and corn, and remaining forest reserves that allowed for comparisons of hydrological and biogeochemical processes between watersheds draining single- and double-cropped cropland and watersheds draining intact forests. We measured surface soil infiltrability and subsurface soil hydraulic conductivity in croplands and forests and used comparisons with rainfall intensities to infer the potential for erosion-generating surface runoff. We measured different forms of extractable N and P in soil profiles to detect vertical nutrient movement through soils. We also gaged headwater streams in different land uses to determine the distribution of base flows and storm flows. By combining stream flow with regular measurements of streamwater sediment and solute concentrations, we estimated annual watershed exports.

We found that soil infiltrability and soil saturated hydraulic conductivity were lower in soybean cropland compared with the native forest, but these values remained high enough to allow surface infiltration of even the most intense rains (Scheffler, Neill, Krusche, & Elsenbeer, 2011). Under current cropping regimes, soils in this landscape are sufficiently permeable to avoid generating the horizontal water flows, surficial gullying, and erosion that occur commonly in Amazon pastures (Biggs, Dunne, & Muraoka, 2007; Germer, Neill, Krusche, & Elsenbeer, 2010). Further evidence of minimal erosion potential was that Tanguro Ranch managers removed all contour berms on the farm, just 2 years after installing them in 2011 (Figure 1).

High infiltration rates through deep soils were consistent with the groundwater-dominated patterns of stream flows we observed in the region. Although total flow in headwater streams was approximately four-fold higher in cropland compared with forest, peak stream discharges in watersheds draining croplands varied little between the wet and dry seasons despite little or no rain for 3 to 4 dry season months (Hayhoe et al., 2011). Storm flows were small and about 95% of annual discharge occurred as base flow. These nonflashy stream hydrographs caused little increase in sediment transport despite a large increase in total flow from cropland compared with forest (Riskin et al., 2017).

Despite inputs of up to more than 200 kg N ha^{-1} that occur by fixation under soybean cropping

Figure 1. The commercial cropland landscape at Tanguro Ranch in Mato Grosso. Lighter soil strips are locations where contour erosion control berms were removed in 2013 (2 years after installation) to facilitate planting and harvesting. The utility of contour berms was limited because very high rates of soil water infiltration minimized surface runoff. Dark linear features running through cropland are headwater streams and adjacent riparian forests within cropland watersheds. Photo: P. Brando.

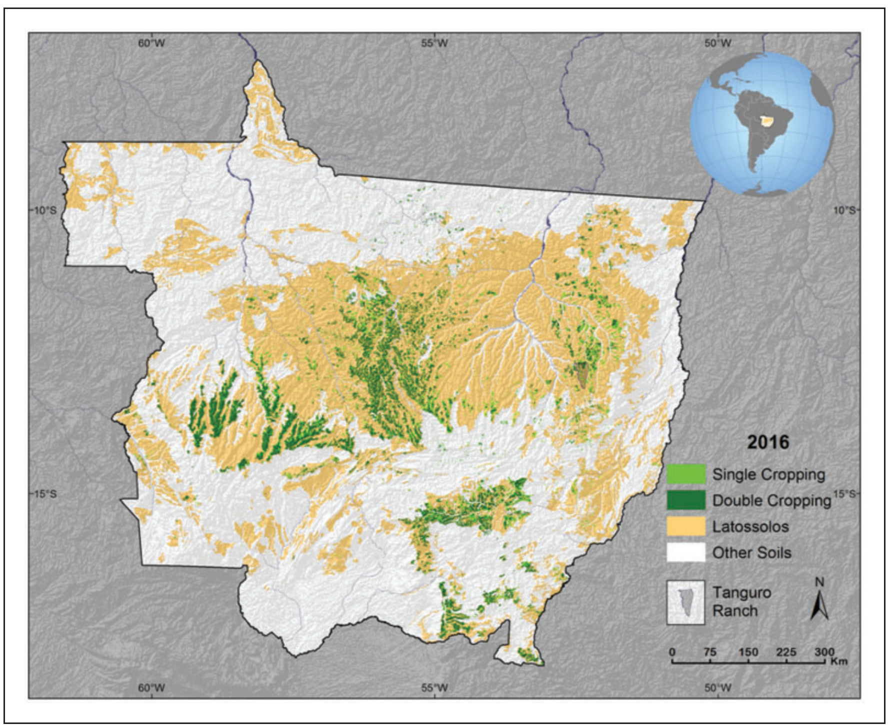

Figure 2. Map of current area of double-cropping and the distribution of major soil types in Mato Grosso illustrating that most double-cropping occurs on deep, weathered soils (Latossols in the Brazilian classification, Oxisols in the US Soil Taxonomy). Double-cropping area updated from Spera et al. (2014) and soil distribution from IBGE-EMBRAPA (2001). The gray triangle in eastern Mato Grosso is the outline of Tanguro Ranch.

(Ferreira et al., 2016), we observed no increase in the concentration of dissolved inorganic N in headwater streams. Watershed N losses increased in proportion to water flow ($\sim$4$\times$) but remained low ($<1.5\,\mathrm{kg\,N\,ha^{-1}}$) compared with losses observed in many temperate commercial croplands (Riskin et al., 2017). Mechanisms for this retention are not well understood, but are likely related to presence of anion exchange in deep soils

(Bellini, Sumner, Radcliffe, & Qafoku, 1996). We have evidence from Tanguro Ranch that soils can retain hundreds of kg of N as nitrate at 2 to 8 m depths (Jankowski et al. unpublished). Furthermore, we saw little evidence of increased N leaching or higher dissolved inorganic N in groundwater or streamwater in soybean-corn croplands fertilized with up to 200 kg N ha^{-1} compared with single-cropped soybeans that received no N fertilizer (Jankowski et al. unpublished).

Despite high rates of P fertilizer application, we found no movement of P from soils to ground and surface waters. Iron and aluminum-rich soils strongly fix P and despite application of about 50 kg P ha^{-1} as fertilizer, this P is bound in the top 30 cm of soil and does not appear in deeper soil layers (Riskin, Porder, Neill, et al., 2013) or in streamwater (Riskin et al., 2017). Erosion-generating overland flows, which deliver P from farm fields to streams in other settings (Sharpley, Smith, Jones, Berg, & Coleman, 1998), generally did not occur. In contrast with other soybean farming regions, where a fraction of P added in previous years is available to the current crop, the deep soils of the Amazon-Cerrado region create an annual "tax" of additional P required to sustain crop production for the forseeable future (Riskin, Porder, Schipanski, et al., 2013, Roy et al., 2016). While reduced use of P fertilizer would lower costs, protection of surface water from P in runoff can likely be sustained for the near future with careful soil management, and the continued productivity of this cropping system will likely require undiminishing amounts of P fertilizer.

Our work shows that the combination of (a) low erosion, (b) the high P fixation capacity of weathered tropical soils, and (c) the large amount of N retained in deep soils (likely by anion exchange) protect streams from the damaging effects of eutrophication. These mechanisms produce different responses to increased fertilizer use than have occurred in the temperate zone, and targeting intensification of cropping on these soils offers potential to produce fewer impacts than might occur on other soils (Figure 2). Using soils to target where intensification could also applied in tropical Africa (Palm, Neill, Tully, & Lefebvre, 2017; Michelson, 2017). While this creates an opportunity to intensify cropping in the near term, the ultimate fate of applied N fertilizer, total soil N adsorption capacity, and the time horizon over which it can continue to prevent N leaching remain unknown. In addition to water quality, other potential impacts from commercial cropland may be important. These include increased stream temperatures (Macedo et al., 2013), fragmentation and alteration of riparian forests (Laurance et al., 2010; Nagy et al., 2015), modification of sediment loads and floodplain structure in larger streams and rivers caused by greater export of water from headwater watersheds (Latrubesse, Amsler, de Moraes, & Aquino, 2009), large-scale alterations of climate caused by reduced forest cover (Coe et al., 2017), and reductions in crop yield caused by higher temperatures (Cohn, 2017).

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